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Rock glaciers and the geomorphological evolution of deglacierizing mountains

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ABSTRACT

Rock glaciers are an important geomorphic element of glaciated mountain landscapes, but our understanding of their distribution and ages, controls on their development, and their importance in regional mountain hydrology and mountain geomorphic evolution is incomplete. In part, this incomplete knowledge arises through problems associated with identifying rock glaciers on a morphological basis alone, amplified by the multiple ways in which rock glaciers can form in different glacial, periglacial, and paraglacial settings. This study focuses on rock glaciers as a paraglacial mountain landscape element and considers the relationships between rock glaciers and glacial, periglacial, and paraglacial processes. New geomorphic and sedimentary data on different rock glaciers from the Khumbu region of Nepal are presented. These data show that even within a single region, rock glaciers may have varied origins and thus likely ages and different climatic and environmental controls. We argue that rock glaciers in deglacierizing mountains may have a long residence time in the landscape, unlike many other glacially influenced mountain landforms, and can undergo significant morphodynamic changes as glaciated landscapes transition into paraglacial landscapes.

1. Introduction

Despite much recent research (e.g., Brenning, 2005; Rangecroft et al., 2015; Jones et al., 2018), the role of rock glaciers in the hydrology and morphological evolution of deglacierizing mountains remains poorly known. In part this arises from limitations of the different ways in which rock glaciers have been identified, measured, and monitored (Hamilton and Whalley, 1995; Roer and Nyenhuis, 2007; Dall'Asta et al., 2017; Deluigi et al., 2017; Kenner et al., 2018). Remote sensing-based methods are not always able to clearly resolve differences between rock glaciers, debris accumulations such as rockfalls, and glacial moraines (Kenner et al., 2014; Wang et al., 2017); and the issue of mimicry and equifinality applies, especially in the case of rock glaciers (Jarman et al., 2013). In addition, individual studies have not always used consistent methodologies, thus making it difficult to compare results between different areas. Any remote sensing methodology largely depends on the data sets used and their resolutions (spectral and temporal), and this has hindered comparability between studies. Field-based methods of quantifying rock glacier properties, their morphometry, and spatial patterns (e.g., Martin and Whalley, 1987; Humlum, 1996; Ikeda and Matsuoka, 2006) are time consuming and expensive; and many mountain regions globally have not been examined in the field by geomorphologists, although numerous inventories from individual mountain blocks have been produced (e.g., Lilleøren and Etzelmüller, 2011; Krainer and Ribis, 2012; Scotti et al., 2013; Rangecroft et al., 2014; Falaschi et al., 2015; Onaca et al., 2016). As a result, rock glaciers remain one of the most poorly understood mountain landforms (Berthling, 2011). This is particularly the case for inactive (relict) rock glaciers whose age, controls, and longevity are difficult to evaluate and whose evolution is difficult to reconstruct. Recent work has discussed the relationship of rock glaciers to paraglacial (landscape relaxation) processes following deglaciation (Knight and Harrison, 2018) and calculated the water balance and water mass budgets of rock glaciers (Krainer and Mostler, 2002). Other recent work has examined the morphometry, internal properties (Roer and Nyenhuis, 2007; Onaca et al., 2013; Emmert and Kneisel, 2017) and dynamic behaviour of rock glaciers (Konrad et al., 1999; Ødegård et al., 2003; Janke, 2005; Jansen and Hergarten, 2006; Serrano et al., 2010; Müller et al., 2016; Anderson et al., 2018), their sediment sources and transport capacity (Barsch and Jakob, 1998; Humlum, 2000; Humlum et al., 2007), and hydrology (Schrott, 1996; Krainer and Mostler, 2002; Geiger et al., 2014; Rangecroft et al., 2015). Despite these varied foci of rock glacier research, the relationships of rock glaciers to other mountain landforms, and their evolution over time and space, are still poorly known, conceptually and in field contexts (Johnson, 1983; Janke et al., 2015; Knight and Harrison, 2018). This study contributes to this emerging debate on rock glaciers and their morphodynamic significance in deglacierizing

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mountains by considering (i) the relationships of rock glaciers to glacial, periglacial, and paraglacial environments and processes and (ii) specific examples of rock glaciers in the Nepalese Himalayas that illustrate the varied geomorphic settings in which they can develop and with implications for long-term mountain landscape evolution. A key conclusion of this study is that not all rock glaciers exhibit the same sensitivity to climate forcing, depending on their genetic origin(s), and that glaciological versus slope versus climatic controls on rock glacier evolution vary through the rock glacier life cycle. This means that different rock glaciers cannot be compared uncritically to one another or used as equivalent sources of information when it comes to comparing the geomorphology or climatic evolution of different mountain regions worldwide.

Table 1
Examples of rock glaciers that have formed from a certain dominant overall environmental domain or set of processes associated with that environmental domain.

Dominant genetic origin of rock glacier	Example location	Reference source
Glacial (by debris burial of glacial ice)	Yukon, USA	Johnson, 1980
	Stubai Alps, Austria	Krainer and Mostler, 2000
	Upper Valtellina, Italian Alps	Guglielmin et al., 2004
	Tröllaskagi, Iceland	Lilleøren et al., 2013
	Andes, central Chile	Monnier and Kinnard, 2015
	Andes, central Chile	Janke et al., 2015
Periglacial (by development of permafrost)	Vanoise Massif, French Alps	Monnier et al., 2013
	Ötzal Alps, Italian Alps	Krainer et al., 2015
Paraglacial (by development of talus slope deposits)	Yukon, USA	Johnson, 1984
	West Greenland	Humlum, 2000
	Sierra Nevada, USA	Millar et al., 2013
	Svalbard	Hartvich et al., 2017

2. Methodology and approach

The first part of this study is conceptual and is based upon a critical analysis of previous work on rock glaciers, supplemented by observations by the authors from active and relict rock glaciers worldwide, including in Europe, South America, and the Himalayas. The second part of this study is based on new remote sensing and field evidence from the Khumbu area of the Nepalese Himalayas, which focuses on mapping the distribution and extent of rock glaciers in the region and on understanding the relationship between debris-covered glaciers and rock glaciers based on their formational setting and geomorphic and sedimentary properties. Rock glacier mapping was achieved using fine spatial resolution satellite image data accessed through Google Earth. Platforms used were SPOT, QuickBird, Worldview-1, Worldview-2, and IKONOS. Geomorphic mapping was done mainly by onscreen digitising and verified during fieldwork (Jones et al., 2018). The context for the second part of this study is the critical interplay between glacial, periglacial, and paraglacial (rockfall sediment supply) processes in the development and dynamics of rock glaciers in this region (e.g., Scherler et al., 2011; Jones et al., 2018), which are in turn critical for regional water supply and geohazard risk (Immerzeel et al., 2010; Kraaijenbrink et al., 2017).

3. Rock glaciers: Environmental domains and evolutionary relationships

The different origins of rock glaciers have been debated for several decades (e.g., Barsch, 1977; Martin and Whalley, 1987; Berthling, 2011). Many rock glaciers can be viewed as polygenic landforms formed mainly during ice retreat (deglacial) phases in deglacierizing mountains, although they are also known to form in nonglacial, periglacial environments (Hamilton and Whalley, 1995). As a result, several different classification schemes of rock glaciers have been identified based on their morphology, dynamic behaviour, geomorphic setting, or some combination of these properties (Martin and Whalley, 1987; Hamilton and Whalley, 1995). For example, Johnson (1984) classified rock glaciers into simple glacial and nonglacial types, influenced by high-magnitude geomorphic events. Giardino and Vitek (1988) identified rock glaciers as transitional landforms of glacial or periglacial types, evolving from debris from glaciers or slopes, and evolving to moraines and slope deposits respectively. Janke et al. (2015) classified rock glaciers into three types, derived from variations in ice content evaluated using remote sensing methods. In summary, different rock glacier classification schemes exist but these are usually mutually exclusive, applied to only a single area or region, and examine different combinations of physical or dynamical properties. To better integrate these ideas together, Table 1 shows examples of rock glaciers formed in different environmental domains, or formed or controlled by a set of processes associated with that particular environmental domain. Although largely polygenic, most rock glaciers reported in the literature are dominated by certain sets of processes, which may reflect their evolutionary history or dominant regional climate regime (Giardino and Vitek, 1988). The classification scheme adopted here builds from Humlum (1988), who distinguished between rock glaciers of dominantly glacial origin (controlled by snow accumulation) and periglacial origin (controlled by ground temperature) (e.g., Ishikawa et al., 2001). Here, we add a further category, which describes rock glaciers of dominantly paraglacial origin, controlled by increased slope sediment supply during regional deglaciation. Rock glacier development in these three different environmental domains is now examined.

3.1. Glacial origins

Rock glaciers can be formed at a valley glacier terminus by upward shearing of subglacial sediments followed by ice stagnation; coverage of the ice surface by supraglacial debris derived from valley sides; ice stagnation and downwasting leading to increased sediment concentration within the remaining ice; and by transformation of ice-cored moraines by mass movements or melting of internal ice, resulting in increased sediment concentration. Rock glaciers therefore usually develop at the onset of glacier retreat or stagnation, and at the front of valley glaciers, and are thus found in particular temporal and spatial contexts. In this environmental setting, rock glaciers mimic a valley glacier terminal moraine. Notably, rock glaciers do not develop at the termini of larger ice caps or ice sheets, largely because of a lack of adequate sediment supply. In the NW European Alps, glacier-derived rock glaciers have developed as a result of rockfalls onto steep glacier surfaces, and this is confirmed by electrical resistivity tomography (ERT) profiles (Bosson and Lambiel, 2016). Here, ablation rates beneath the debris cover are around 40 times lower than on adjacent debris-free areas of the glacier surface, amplifying rock glacier response under conditions of climate warming and glacier thinning. Similar patterns are observed in eastern Nepal where rock glaciers have evolved from inactive glaciers, particularly at the transition zone to discontinuous permafrost (Ishikawa et al., 2001). In the Andes of central Chile, the transition from glaciers to rock glaciers is dependent on supraglacial debris thickness, and thus the morphodynamic distinction between these types is related to whether surface debris has vertical and horizontal velocities different to those of the underlying glacier (Janke et al., 2015). This definition of a glacial ice-derived rock glacier also holds for examples from Yukon, USA (Johnson, 1980).

3.2. Periglacial origins

The most common genetic origin reported for rock glaciers globally is in association with the periglacial environmental domain and linked to the development, maintenance, and seasonal dynamics of permafrost and the active layer. Many studies suggest that the lowermost

altitudinal limit of rock glaciers coincides with the lowermost altitude of permafrost within that mountain massif (e.g., Krainer and Ribis, 2012; Bolch and Gorbunov, 2014; Rangecroft et al., 2014; Sattler et al., 2016; Esper Angillieri, 2017) and that this is a deterministic relationship whereby rock glacier distribution can be used as a proxy for permafrost distribution and vice versa (e.g., Uxa and Mida, 2017). Although not helpful as an approach and based on circular reasoning, this relationship also alludes to the role of seasonal development of the active layer in the dynamics of rock surface features, including the development and flow velocities of furrows and lobes (Kääb and Weber, 2004; Haeberli et al., 2006; Frehner et al., 2015). These features have been used as a diagnostic indicator of the presence of ice-rich permafrost within the rock glacier body. Ground-penetrating radar and ERT methods have also been used to image and map subsurface permafrost bodies within the rock glacier. These methods can highlight the internal permafrost surface, variations in permafrost/snow temperatures and moisture, and debris concentrations (e.g., Isaksen et al., 2000; Hausmann et al., 2012; Monnier et al., 2013). Radiocarbon dating of plant macrofossils within the permafrost core of a rock glacier in the Ötztal Alps, Italy, shows that at 23.5 m depth, the permafrost is 8960 years old; whereas, at 2.8 m depth it is 2240 years old (Krainer et al., 2015). However, the presence of variable ice fabrics and shear planes within rock glacier bodies (e.g., Isaksen et al., 2000; Bucki and Echelmeyer, 2004; Krainer and Mostler, 2006) means that such chronologies cannot be used uncritically in this instance to infer that the rock glacier is of early Holocene age or that it has existed in the same state during this time period.

Changes in the position of fixed points on the rock glacier surface have been used as a method to track horizontal and vertical displacements of the rock glacier over time (e.g., Whalley et al., 1995; García et al., 2017). Depending on sampling interval, this method can show seasonal variations in rock glacier surface morphologies that can inform on permafrost active layer dynamics (Kellerer-Pirklbauer and Kaufmann, 2012). In addition to rates of surface flow determined by internal deformation of permafrost ice, slower or faster surface rates can be described based on compression and extension respectively within the rock glacier body (Kääb and Weber, 2004). Bucki and Echelmeyer (2004) suggested that higher and more variable rates of rock glacier surface velocities may be caused by the ice–rock mixture present. The reason for this is that ice and rock have different thermal and compressive strength properties and thus can become disaggregated during differential three-dimensional flow that promotes internal deformation of the rock glacier body (Humlum, 1997). There is also differential movement within and between snow/ice units of different origins and rheologies (Haeberli et al., 2006).

3.3. Paraglacial origins

Rock glaciers can develop in a paraglacial context where rockfalls, rock slides, and other mass movement processes taking place on bedrock outcrops or on steep slopes can contribute material to debris piles located at the outcrop foot. This debris can also be detached by periglacial frost wedging. The debris can be included within snowbanks or onto dead glacier ice or permafrost located at the slope foot, which can ultimately lead to formation of a rock glacier of dominantly paraglacial origin. The role of rockfalls and other mass movements to rock glacier formation has been identified in particular high-relief mountains with narrow valleys (e.g., Johnson, 1984; Hartvich et al., 2017) and where constricted valley glaciers are undergoing rapid downwasting in response to climate change. The relative timing of rockfall and other mass movement events in such settings has commonly been reconstructed using Schmidt hammer exposure dating (Hedding, 2016; Hartvich et al., 2017) or cosmogenic dating methods (Ciner et al., 2017; Winkler and Lambiel, 2018). In some regions, sediment supply rates by mass movements are strongly affected by slope aspect, in which slopes with a greater diurnal temperature regime result in higher weathering and sediment supply rates (Johnson et al., 2007; Nagai et al., 2013). In turn, this should result in distinctive spatial patterns of rock glacier distributions that correspond to paraglacial slope sediment supply - Nagai et al. (2013) reported that southwest-facing slopes in the Bhutan Himalaya are most strongly associated with glaciers with high frost shattering-derived debris accumulations. In other sites where paraglacial rockfalls dominate debris supply to valley bottoms, rock glacier distribution reflects the orientation of steep rock walls that are shedding rock debris.

The large size and angularity of much debris derived from slope processes mean that paraglacial rock glaciers have surface debris that is potentially coarser when compared to rock glaciers that have other origins. Here, the paraglacial rock glaciers have a steeper frontal slope, and exhibit lower velocities of movement when compared to other rock glacier types. Further, as paraglacial rock glaciers are usually backed by a steep backwall sediment source, they may evolve over time by forward movement of the rock glacier front (rock glacier thinning) or by increased sediment supply (rock glacier thickening). Several studies have been concerned with the processes of in situ water/ice accumulation in the pore spaces of coarse rockfall/talus debris. This can take place by spring-fed water supply at the talus slope base, infiltration by snowfall, or advective cooling and associated moisture freezing within the debris body (Krainer and Mostler, 2002, 2006; Millar et al., 2013; Kellerer-Pirklbauer et al., 2015; Popescu et al., 2017).

3.4. Developing a model for rock glacier evolution

Rock glaciers are equifinal landforms inasmuch as they can develop as a consequence of glacial, periglacial, and paraglacial processes, individually or in combination. Based on the foregoing discussion of different rock glacier types and their properties, a genetic classification model can be proposed to describe the corelationships between different controls on rock glacier origin and evolution (Fig. 1). This typological model shows that rock glaciers of glacial origin are mainly controlled by water availability; those of periglacial origin are mainly controlled by temperature; and those of paraglacial origin are mainly controlled by sediment supply. Although this is a nonexclusive classification and links exist between these process domains, the model can also show the different evolutionary pathways undertaken by individual rock glaciers described in the literature (Fig. 1). For example, pathway 1 corresponds to rock glacier development by increased debris content at a stagnating glacier margin, by subglacial thrusting or supraglacial debris accumulation, or by transformation of an ice-cored moraine. Pathway 2 corresponds to a situation where the footslope of a talus cone or scree increases its water content over time by water percolation and freezing or by interstitial snow accumulation. Pathway 3 corresponds to a situation where buried glacier ice transforms into a seasonal active layer where there is high enough interstitial moisture content to allow for

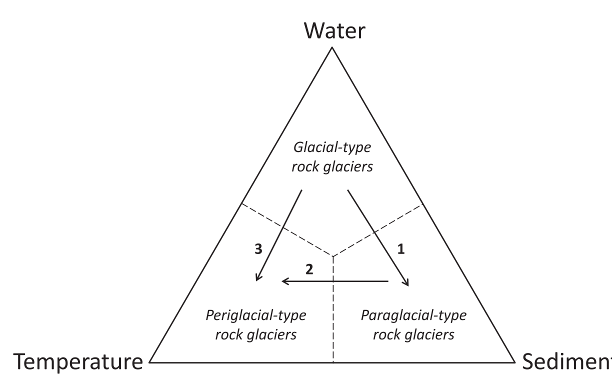

Fig. 1. Ternary diagram illustrating a conceptual classification of different rock glacier types according to their dominant modes of origin. Evolutionary pathways 1–3 are discussed in the text.

seasonal meltwater advection through the debris layer. In sum, several different evolutionary pathways are theoretically possible, and individual examples of rock glaciers of these types have been described from the literature from different mountain blocks and climatic/glaciological settings worldwide. What remains unclear, however, is whether rock glaciers from a single region display such evolutionary diversity. It is important to answer this question because it is generally assumed that rock glaciers from a single region – displaying broadly the same climatic, geologic, and glacial conditions – will have the same controls on their development. We now test this assumption against field data from a single region of the Nepalese Himalayas where large numbers of rock glaciers of different shapes and sizes have been mapped from remote sensing and field observations.

4. Rock glaciers in the Himalayas: their classification and evolution

In the Himalayas, rock glaciers have been widely observed; and their physical characteristics can be used to test a model of formation in dominant glacial, periglacial, or paraglacial settings. For example, Iwata et al. (2003) discussed a range of periglacial evidence from N and NW Bhutan that is related to the presence of permafrost and rock glaciers. They identified rock glaciers that have glacial or periglacial origins and that may be either active or inactive (relict). Of these, only 9% (3) had glacial origins, the majority being periglacial. Most were active, but 22% (7) were deemed inactive. Several studies have produced rock glacier inventories in different sectors of the Himalayas (e.g., Shroder et al., 2000; Ishikawa et al., 2001; Jones et al., 2018). These studies do not

Fig. 2. Khumbu Himal, Nepalese Himalaya. (A) Google Earth satellite image (11 March 2009) of rock glaciers and other features situated in the Khumbu valley. Values (m asl) reflect the elevation of rock glacier termini. The dominant environmental domain is also detailed for each rock glacier. A transitional feature (Chola glacier) is also delineated. For the distribution of moraines and alluvial fans around the Khumbu Glacier terminus, please refer to Barnard et al. (2006). Annotated photographs of (B) Chola glacier; (C) Pokalde rock glacier (PO); (D) Lingten rock glacier (LI); (E) examples of rock slope failure and Little Ice Age moraine collapse, likely resulting from debuttressing following Khumbu glacier downwasting. Kongma rock glacier is also depicted (photos: D.B. Jones).

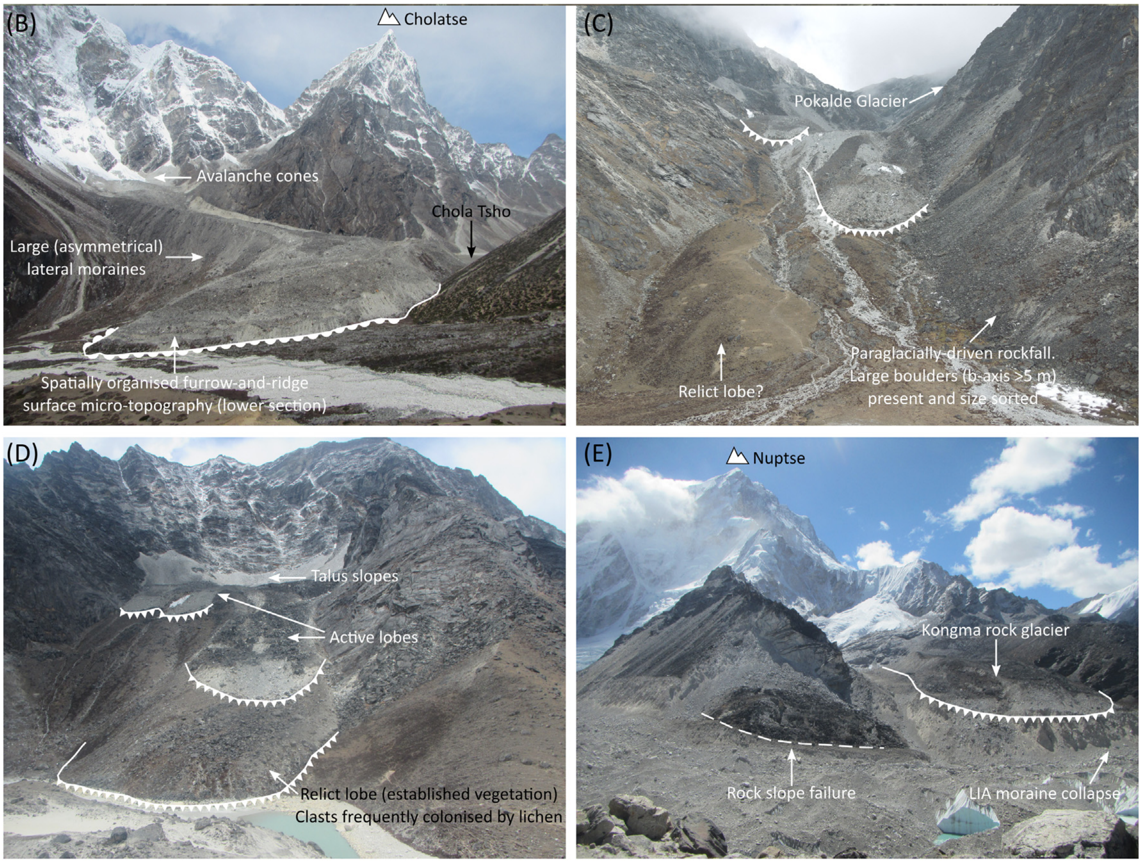

Fig. 2 (*continued*).

show a simple distinction by height or aridity gradient, suggesting that the distribution of rock glaciers as a whole is not controlled by the current climate regime but broadly reflects antecedent conditions (Sorg et al., 2015). Previously mapped rock glaciers in the region may also have been misinterpreted (Fort, 2003). The suggestion that active rock glaciers represent the lowermost limit of permafrost (e.g., Iwata et al., 2003) is a circular argument and must be discarded in terms of evaluating rock glacier origins.

Several phases of glaciation during the late Quaternary took place in the Khumbu Himal study area of eastern Nepal, with the most recent glacier retreat and moraine formation around the Khumbu Glacier and adjacent glaciers taking place around 1000–1200 y BP, known as the Lobuche Stage (Richards et al., 2000). Alluvial fans and terraces located <5 km down the Khumbu Glacier valley have been dated by the cosmogenic method to different intervals at 16, 12, 8, 4, and 1.5 ky BP, corresponding to different phases of ice retreat (Barnard et al., 2006). The precise age of development of rock glaciers in the region is uncertain due to lack of exposure dating (e.g., Benn and Owen, 2002; Zech et al., 2009), but they likely correspond to these periods of ice retreat and land surface exposure. The Khumbu Glacier has experienced an increase in debris content in recent years at the glacier terminus (Nakawo et al., 1999).

In the Khumbu Himal region, rock glaciers have been extensively mapped using a combination of remote sensing and field mapping. The major properties of these rock glaciers and their genetic origins have been examined in several studies (e.g., Barsch and Jakob, 1998; Iwata et al., 2003). Other studies have also been concerned with the surface debris content and distribution on valley glaciers in the region, with the purpose of identifying variations in spatial patterns of debris content over time (e.g., Nakawo et al., 1999; Hambrey et al., 2008; Rounce and McKinney, 2014; Rowan et al., 2015; Schauwecker et al., 2015). In summary, the Khumbu region contains many rock glaciers of different types (Jones et al., 2018); however, there is a lack of information on their detailed geometric, morphological and sedimentary properties that can inform on rock glacier origin. New evidence of rock glacier distribution and properties in this region is now presented, based on original fieldwork and supplemented by spatial data analysis from remote sensing.

A number of rock glacier examples are found within the Khumbu Himal region (Fig. 2). In the field, Pokalde rock glacier (PO), Lingten rock glacier (LI), and Chola debris-covered glacier were investigated in detail. The Lingten rock glacier is located at ~4940 m asl and extends from talus slopes beneath a high (~400–500 m), steep headwall (Fig. 2D). The rock glacier has a steep (>30–35°), high (>30–40 m) and sharp-crested frontal slope, light-coloured frontal slope that suggests little clast weathering, and no vegetation cover (Fig. 3A). These characteristics suggest that the upper lobes contain frozen material and are seasonally active. Conversely, the lowermost lobe has extensive vegetation cover with boulders that are weathered and lichen-covered, indicating long-term stability (i.e., the rock glacier contains no ice). Lingten rock glacier has an active layer composed of blocky matrix-free boulders (Fig. 3B) and thus can be termed a 'bouldery rock glacier' according to Ikeda and Matsuoka's (2006) classification. Additionally, large, angular rockfall debris (Fig. 3C) and perched boulders are commonly present. Previously, Regmi (2008) classified Lingten rock glacier as a periglacial feature based on remote sensing data; however, its morphological and debris characteristics suggest that it has a paraglacial origin. Within this region, only Dughla rock glacier (DU) was classified as having a periglacial origin. Previous studies show that this rock glacier is active with an average velocity of 4.0 to 8.5 cm y^{-1} and this is reflected in its 35–40° steep frontal slope (Jakob, 1992; Barsch and Jakob, 1998).

The hitherto unnamed Pokalde rock glacier is a glacier-derived rock glacier, thus is of glacial origin, located at ~5030 m asl with a west-facing aspect (Fig. 2C). Rock glacier morphology (e.g., relatively flattened rock glacier body and gently sloping front of <30°) and minor vegetation

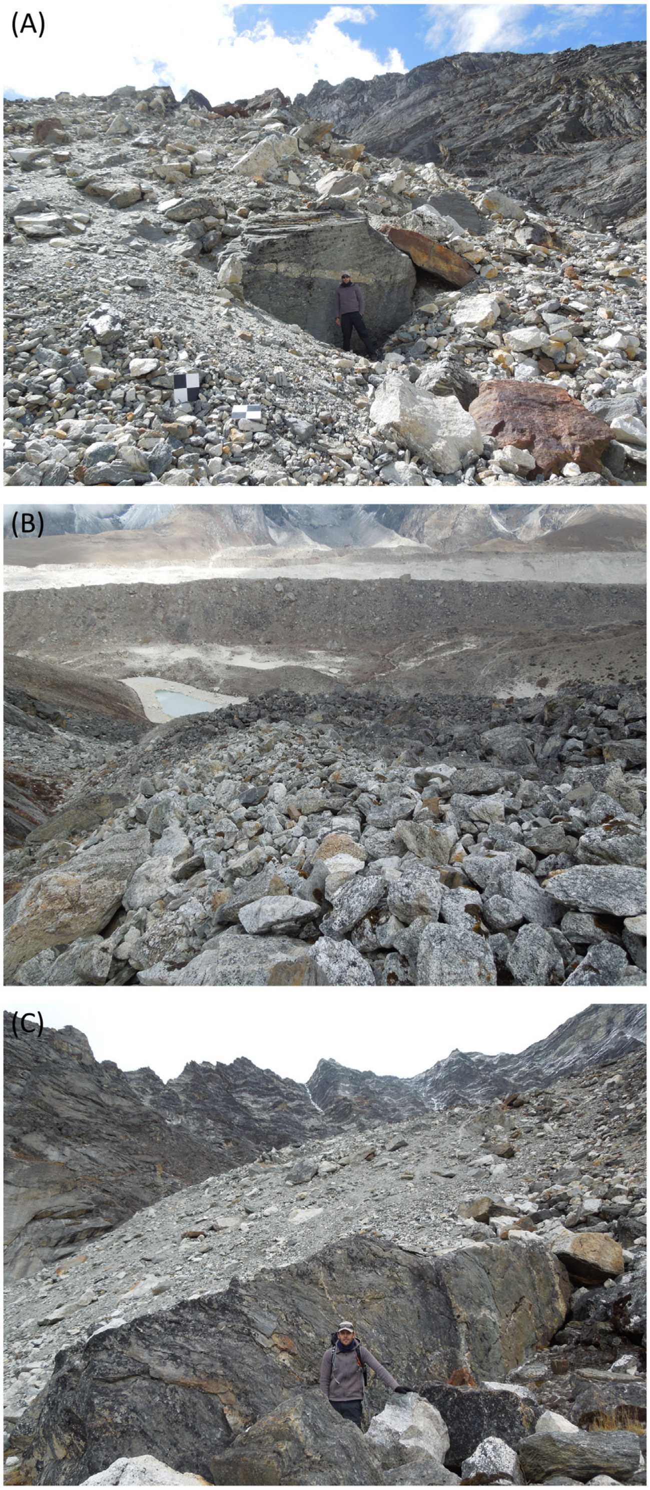

Fig. 3. Ground views of Lingten rock glacier surficial characteristics including (A) the steep, high, sharp-crested and vegetation-free frontal slope indicating an active rock glacier; (B) the large blocky clasts forming the active layer; (C) evidence of large rockfall-derived debris. Note also the high headwalls in the image background (photos: D.B. Jones).

cover suggests that the Pokalde rock glacier contains frozen material but displays no contemporary movement. The clean Pokalde Glacier is situated immediately upslope of this rock glacier and has receded considerably in recent years. Paraglacial processes are evident in the vicinity of the rock glacier (see Fig. 2C) with angular (and occasionally large) perched boulders resulting from rockfall (Fig. 4). While Pokalde rock

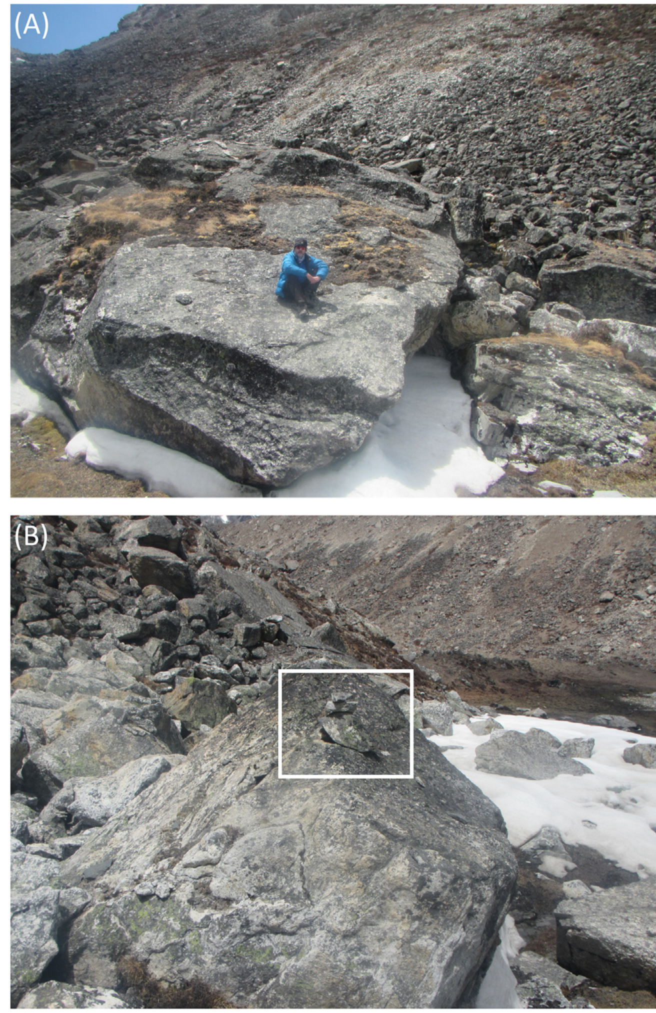

Fig. 4. Paraglacially driven rockfall evidence beneath Pokalde rock glacier. (A) Angular, large debris with smaller clasts in the background suggesting a degree of fall sorting; (B) perched boulders (photos: D.B. Jones).

glacier has developed in a glacial process domain, this evidence suggests paraglacial processes may have also sustained the rock glacier. Large-scale rock slope failures, suggesting paraglacial relaxation of entire slopes (rather than individual detachment of frost-wedged blocks), are also recorded nearby (Fig. 2E).

The most conspicuous geomorphological expressions of glacier–rock glacier relationships are large composite landforms that form as debris-covered glaciers and then transition into rock glaciers (e.g., Ribolini et al., 2007; Emmer et al., 2015; Janke et al., 2015; Monnier and Kinnard, 2015, 2017; Seppi et al., 2015). Geomorphological field surveys suggest that the tongue of Chola debris-covered glacier (Fig. 2B) is transitioning to a glacier-derived rock glacier. Similar to the Presenteseracae debris-covered glacier in the Chilean Andes (Monnier and Kinnard, 2015), the Chola debris-covered glacier has developed a characteristic rock glacier morphology (i.e., a spatially coherent furrow-and-ridge surface morphology) in its lowermost part. Additionally, the surface is characterised by very large (>4 m), angular boulders and a thick debris layer, indicating movement to the snout of rockfall-derived material (Fig. 5). Such evidence of paraglacial processes suggests that glacier–rock glacier composite landforms in at least part of the Himalayas are the product of glacial and paraglacial environmental domains (cf., Scherler et al., 2011; Nagai et al., 2013; Babu Govindha Raj, 2017).

Geomorphological mapping of rock glaciers in the Khumbu region can be supplemented by clast analysis of their constituent debris as a tool to discriminate between rock glacier types. This is a useful

Fig. 5. Ground-based view of the lowermost part of the Chola debris-covered glacier (photo: D.B. Jones).

methodology because clast shape properties can identify their source areas in glaciated environments and specifically can distinguish between subglacial and supraglacial debris sources (Lukas et al., 2013). Measurements of individual clasts can be used to derive the RA ratio (the percentage of angular and very angular clasts in any sample) and the C_{40} index (the ratio of *c*/*a*-axis lengths ≤0.4). These are the two most useful parameters to distinguish clast source (Benn and Ballantyne, 1993). Results from the Khumbu region are presented in Fig. 6. High RA and C_{40} values are typical of unmodified clasts formed by periglacial frost-shattering (Benn and Ballantyne, 1994). Notably, Pokalde rock glacier has significantly lower values than the other two sites examined, with no overlapping geometrical properties (Fig. 6E), suggesting a different sediment source and a stronger geological control on sediment supply. These sedimentary data in combination with the geomorphic properties and landform associations of the rock glaciers discussed above suggest that debris making up Chola glacier and Lingten rock glacier is derived from steep, frost-shattered bedrock slopes; whereas debris making up Pokalde rock glacier is glacier-derived. Thus, despite both having cores of glacial ice, Chola and Pokalde have very different debris sources.

This summary of different rock glacier properties from the Khumbu region shows that – even within a small area with uniform climatic, glacial, and geologic conditions – a variety of rock glacier types and origins can coexist. In detail, the reasons for such variability relates to microscale climatic variations caused by aspect; valley glacier width and bedrock slope (determining the likelihood of ice margin stagnation); antecedent conditions including whether glaciers or permafrost are growing or are in retreat; and proximity of the rock glacier to a potential rock-slope sediment source (rock wall height and distance) (e.g., Shroder et al., 2000; Ishikawa et al., 2001; Fort, 2003; Nagai et al., 2013; Jones et al., 2018).

5. Discussion

Rock glaciers are equifinal polygenic landforms and are key elements of the geomorphology of cold mountains worldwide, but the different evolutionary pathways by which rock glaciers develop remain unclear. This is particularly the case where rock glaciers in the same area such as the Khumbu region show different geometries and physical properties. The proposed classification of rock glaciers globally into broad glacial, periglacial, and paraglacial process domains identifies three different rock glacier end-members (Fig. 1). Within this, however, rock glaciers can evolve over time from one dominant process domain to another as a result of variations in sediment supply and climate (temperature and moisture availability) in combination. This means that there are limitations to the extent to which rock glaciers can inform on regional climate variability, or stages of regional glacier retreat, given that their geometry and morphodynamics may be more strongly controlled by other factors, such as aspect and antecedent conditions. This highlights that previous analyses of rock glacier inventories may have little scope for speaking to any single overarching theory for rock glacier formation because they may have limited applicability outside of their region of origin. This also means that the presence of relict rock glaciers in a region cannot be used uncritically in palaeoclimate reconstructions.

Studies of different rock glaciers from the Himalayas show their complex time evolution and morphological relationships to glacial and slope (paraglacial) landforms and processes (e.g., Owen and England, 1998; Shroder et al., 2000; Ishikawa et al., 2001; Fort, 2003; Iwata et al., 2003; Nagai et al., 2013; Sorg et al., 2015; Jones et al., 2018). These varied controls mean that no one single evolutionary model applies to describe rock glaciers in this region. A better context for explaining their development is to consider them along the continua of variations in sediment supply and climate that drive their morphodynamic trajectory (Fig. 1), and this approach can provide a classification and interpretative framework for all rock glaciers globally, irrespective of origin. By way of illustration, we have located on this model the examples described in the text from the Khumbu region (Fig. 7). This suggested genetic classification of the different rock glaciers shows that they are of different types, that they do not have the same origins, drivers, and sensitivities and that this is of significance for evaluating the geomorphic evolution of deglacierizing mountains worldwide.

The proposed evolutionary model of rock glacier development (Fig. 7) also speaks to the evolution of rock glaciers through their varied life stages. This has not been adequately discussed in the literature. Although several studies identify rock glaciers as transient landforms found in deglacierizing terrain (e.g., Giardino and Vitek, 1988; Ballantyne, 2002a; Berthling, 2011; Monnier and Kinnard, 2017; Knight and Harrison, 2018), these rarely expand upon what this means in practice. Relationships between the three rock glacier types according to their dominant mode of origin (Fig. 1) can change over time and space. Upon deglaciation, water availability within the interstices of rock glacier debris decreases, following the trajectory of evolution of Chola debris-covered glacier illustrated in Fig. 7. Thus, it may be that glacial- and periglacial-dominated rock glaciers transition to paraglacial types and that paraglacial rock glaciers can be considered as the final evolutionary stage of all rock glaciers in a deglacierizing mountain landscape. Despite these different rock glacier types, their temporal relationships, even within a single region, are uncertain; and there is no unidirectional trajectory from one type to another. Cosmogenic dating of clasts on rock glacier surfaces can be problematic because surficial clasts could be added by episodic rockfall at any time (producing young or inherited ages), and cryoturbation of clasts within the rock glacier body can take place during its movement, exhuming older clasts from below (producing anomalously old ages) (Ciner

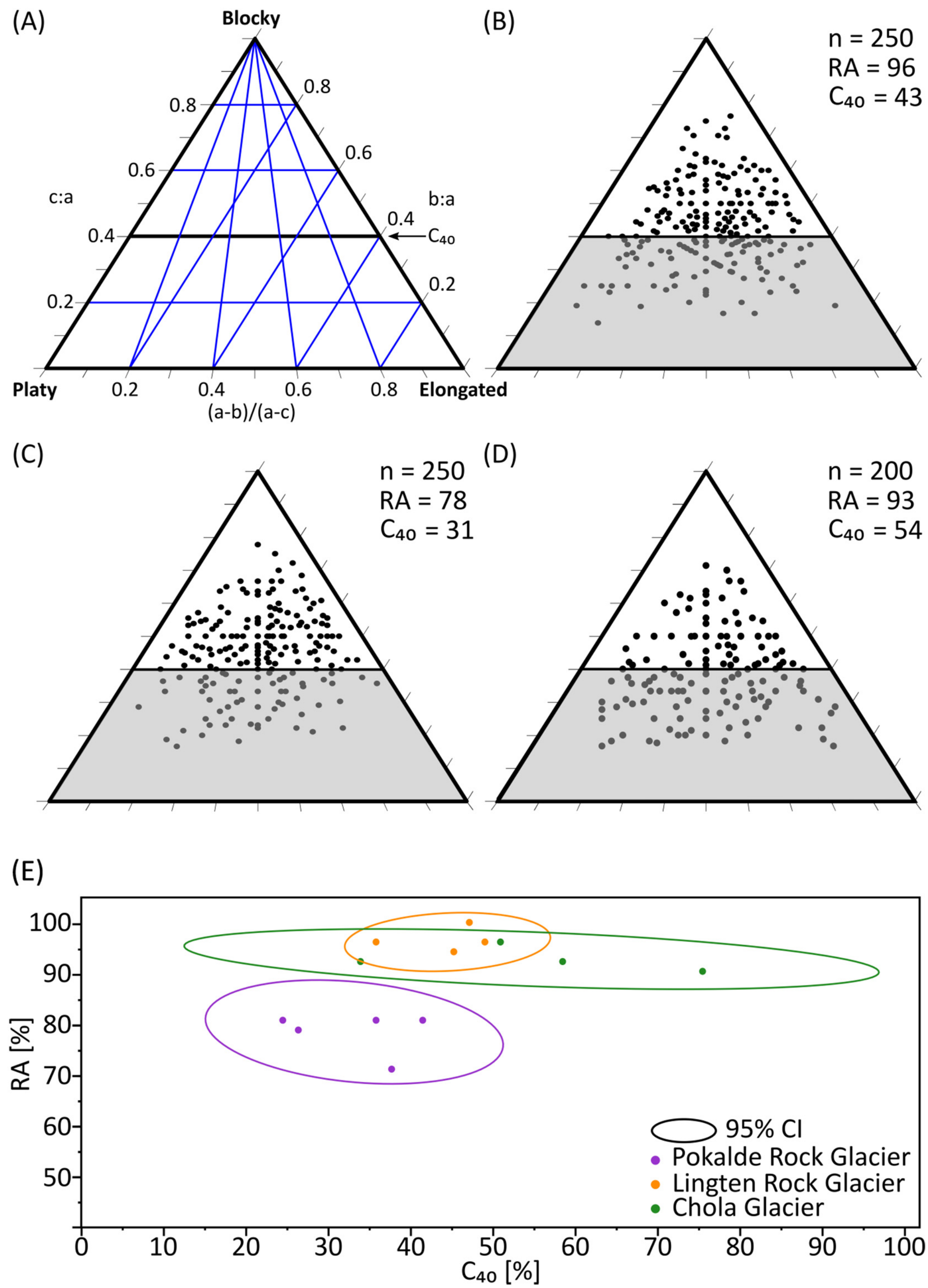

Fig. 6. (A) Schematic ternary diagram, depicting axial ratios and clast end member states, and clast shape data from three sampled landforms: (B) Lingten rock glacier; (C) Pokalde rock glacier; and (D) Chola glacier. Abbreviations: n = number of clasts sampled; RA and C_{40} are defined in the text. (E) Summary RA–C_{40} bivariate scatterplot of the features sampled in situ. Envelopes (ellipses) reflect the 95% confidence interval of each data group.

et al., 2017). Also, any determination of rock glacier age cannot unequivocally inform on rock glacier origin. This is because glacier ice can exist within the rock glacier body long after the glacier itself has melted away (Monnier et al., 2013; Krainer et al., 2015); glacial and periglacial (permafrost) processes can coexist during the rock glacier's life; and periglacial and paraglacially enhanced slope sediment yield can exist for thousands of years after deglaciation (Ballantyne, 2002b).

5.1. Geomorphic sensitivity and landscape change in deglacierizing mountains

Paraglacial relaxation of unstable rock slopes is increasingly being recognized as an important component of deglacierizing mountains (e.g., Ballantyne, 2002a, 2002b; McColl, 2012; Knight and Harrison, 2014; Beniston et al., 2018). Paraglacial processes include large-scale

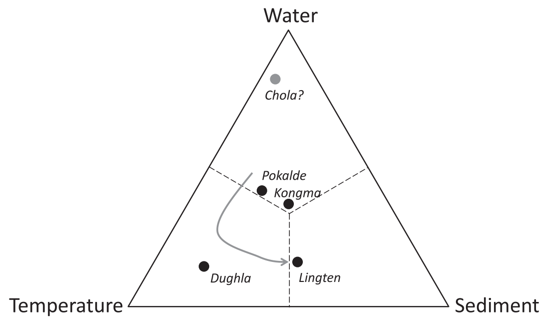

Fig. 7. Rock glaciers in the studied Khumbu region, Nepal, and their suggested positioning on the schematic ternary diagram presented in Fig. 1. The likely evolutionary trajectory of Lingten rock glacier discussed in the text is shown by the grey arrow.

rock slope failures as well as more localized rockfalls, landslides and debris flows. These contribute to high slope sediment yields accompanying ice retreat. This paraglacial response is important because it affects first mountain glaciers and, then, mountain rock glaciers.

Studies show that Himalayan glaciers are experiencing increased debris cover and debris thickness as a result of increased recent slope sediment supply (Hambrey et al., 2008; Scherler et al., 2011; Rowan et al., 2015; Schauwecker et al., 2015; Lamsal et al., 2017). Surface debris can variously amplify or suppress glacier melting, leading to decreased or increased longevity of debris-covered glaciers respectively, and this affects the likelihood with which debris-covered glaciers can transition to glacial-derived rock glaciers and their resulting dynamics, including any seasonal variations in surface morphological change (Hausmann et al., 2012). Initial high rates of ice melting under a thin debris cover can rapidly switch to low rates of melting if the ratio of debris to ice changes (Ikeda and Matsuoka, 2002; Anderson and Anderson, 2018), and several studies have examined how surface debris thickness and grain size can influence the thermal regime of underlying ice (e.g., Humlum, 1997; Luethi et al., 2017; Anderson and Anderson, 2018). Changing spatial and temporal patterns of nonglacial (paraglacial) sediment supply can thus dramatically impact on glacier dynamics.

A key property in determining the dynamics of rock glaciers is the relative proportions of rock and ice. The former has greatest potential for variability because it depends on the availability of a sediment source (bedrock cliffs located above the rock glacier surface) and the rate of sediment supply (weathering rates, degree of slope instability). In almost all known cases, debris content increases rather than decreases over time at the onset of deglaciation (e.g., Glasser et al., 2016) because debris has lower mobility than water and because of the positive feedback effects that debris has on glacier thermal regime. As a consequence of increased debris concentration, many mountain glaciers worldwide are likely to transition to rock glaciers, as is starting to happen at Chola debris-covered glacier (Fig. 2B) and perhaps also at the snout of Khumbu glacier, which is becoming increasingly charged with debris (cf., Nakawo et al., 1999). Rock glaciers are thus likely to become a more common mountain landform over coming decades/centuries, and their relative geomorphic stability as a latticework of angular debris means that they may have a long residence time in the landscape. Rock glaciers can therefore be viewed as an important extended paraglacial transient stage in mountain geomorphic evolution, between glacial and nonglacial endmembers (Cossart et al., 2017; Knight and Harrison, 2018). Notably, the key role of rock glaciers was not fully considered in previous models of paraglacial landscape change (e.g., Ballantyne, 2002a, 2002b).

6. Conclusions

This study shows that rock glaciers can develop under glacial, periglacial, and paraglacial environmental process domains. Interactions exist between these process domains as deglacierizing mountain landscapes change over time, leading to different evolutionary pathways for different rock glaciers, even within the same region, as shown by examples of rock glaciers from the Khumbu region of Nepal. The role of rock glaciers in mountain landscape evolution has hitherto not been fully recognized, and this is a critical research gap given that studies are now showing that mountain glaciers in the Himalayas and Andes in particular are now transitioning to rock glaciers. It is likely that rock glaciers will become more numerous and more significant in terms of water and sediment storage as climate change proceeds through the twenty first century.

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